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# A WFC3 study of globular clusters in NGC 4150 - an early-type minor merger

Sugata Kaviraj[1,2], R. Mark Crockett[2], Bradley C. Whitmore[3], Joseph Silk[2], Robert W. O'Connell[4], Rogier A. Windhorst[5], Max Mutchler[3], Marina Rejkuba[6], Sukyoung Yi[7], Jay A. Frogel[8,9] and Daniela Calzetti[10]

[1] *Blackett Laboratory, Imperial College London, London SW7 2AZ, UK*
[2] *Department of Physics, University of Oxford, Keble Road, Oxford, OX1 3RH, UK*
[3] *Space Telescope Science Institute, Baltimore, MD 21218, USA*
[4] *Department of Astronomy, University of Virginia, Charlottesville, VA 22904-4325, USA*
[5] *School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287-1404, USA*
[6] *ESO, Karl-Schwarzschild-Strasse 2, 85748 Garching bei Mnchen, Germany*
[7] *Department of Astronomy, Yonsei University, Seoul 120-749, Republic of Korea*
[8] *Galaxies Unlimited, 1 Tremblant Court, Lutherville, MD 21093 USA*
[9] *King Abdulaziz University, Jeddah, Saudi Arabia*
[10] *Department of Astronomy, University of Massachusetts, Amherst, MA 01003, USA*



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## ABSTRACT

We combine near-ultraviolet ($NUV$; 2250Å) and optical ($U, B, V, I$) imaging from the *Wide Field Camera 3* (WFC3), on board the *Hubble Space Telescope* (HST), to study the globular cluster (GC) population in NGC 4150, a sub-L* ($M_B \sim -18.48$ mag) early-type minor-merger remnant in the Coma I cloud. We use broadband $NUV$-optical photometry from the WFC3 to estimate individual ages, metallicities, masses and line-of-sight extinctions ($E_{B-V}$) for 63 bright ($M_V < -5$ mag) GCs in this galaxy. In addition to a small GC population with ages greater than 10 Gyr, we find a dominant population of clusters with ages centred around 6 Gyr, consistent with the expected peak of stellar mass assembly in faint early-types residing in low-density environments. The old and intermediate-age GCs in NGC 4150 are metal-poor, with metallicities less than $0.1Z_{\odot}$, and reside in regions of low extinction ($E_{B-V} < 0.05$ mag). We also find a population of young, metal-rich ($Z > 0.3Z_{\odot}$) clusters that have formed within the last Gyr and reside in relatively dusty ($E_{B-V} > 0.3$ mag) regions that are coincident with the part of the galaxy core that hosts significant recent star formation. Cluster disruption models (in which ~80-90% of objects younger than a few $10^8$ yr dissolve every dex in time) suggest that the bulk of these young clusters are a transient population.

**Key words:** galaxies: star clusters - galaxies: individual: NGC 4150 - galaxies: elliptical and lenticular, cD - galaxies: evolution galaxies: interactions - ultraviolet: galaxies

## 1 INTRODUCTION

Globular clusters (GCs), which are expected to form in all major star-formation episodes (e.g. Kissler-Patig et al. 1998), are important tracers of the stellar mass assembly of their host galaxies. While there is evidence for multiple stellar populations in some clusters (e.g. Piotto 2009; Origlia et al. 2011), the constituent stars in most GCs are, to a reasonable approximation, uniform in age and metallicity. The distributions of GC ages and metallicities therefore trace the entire cosmic star-formation and chemical-enrichment history of their host galaxies. (e.g. Ashman & Zepf 1998; Whitmore 2003; Brodie & Strader 2006, and references therein). The rich literature of optical spectro-photometric studies of GCs is largely focussed on massive early-type galaxies (ETGs) in the local Universe (e.g. Harris 1991; Gebhardt & Kissler-Patig 1999; Larsen et al. 2001; Kundu & Whitmore 2001; Proctor et al. 2004; Strader et al. 2005; Harris et al. 2006), and demonstrates that the bulk of the star formation in these systems takes place at high redshift ($z > 2$), in agreement with studies of their field stellar populations (e.g. Renzini 2006). The relatively recent advent of near-infrared (NIR; Goudfrooij et al. 2001; Puzia et al. 2002; Hempel et al. 2003; Kundu et al. 2005) and ultraviolet (UV; Kaviraj et al. 2007a,b; Rey et al. 2009) data provides improved constraints on intermediate-age and young GCs in some galaxies, which are expected to form as a result of recent merger activity in the hierarchical paradigm (e.g. Beasley et al. 2002; Kaviraj et al. 2005).

The subject of this study is NGC 4150, a sub-L* ($M_B \sim -18.48$ mag) ETG in the Coma I cloud, which is part of the Wide Field Camera 3 (WFC3) Early-Release Science observations (HST Programme 11360, PI: O'Connell). It was imaged in a series of broadband WFC3 filters including F225W (*NUV*), F336W (*U*), F438W (*B*), F555W (*V*), F814W (*I*) - see Table 2 in Crockett et al. (2011, C11 hereafter) for exposure times in each filter. This galaxy has a stellar mass of $6.3{\times}10^9$ M$_\odot$ (C11), $5{\times}10^7$ M$_\odot$ of $M_{H_2}$ (Combes et al. 2007), and exhibits a kinematically decoupled core, indicative of recent merging (Krajnović et al. 2008) and strong, central H$\beta$ absorption, indicative of young stars (Kuntschner et al. 2006, see also Jeong et al. 2009). A recent spatially-resolved study, using WFC3, of its field stellar population indicates that NGC 4150 is a minor-merger remnant, the accretion event creating a low-metallicity ($\sim 0.3-0.8Z_\odot$) stellar component over the last Gyr, that contributes ~3% of the stellar mass in this galaxy (C11).

In this *Letter* we use broadband ($NUV, U, B, V, I$) photometry to explore the ages, metallicities and stellar masses of GCs in NGC 4150. Recent work has shown that photometry shortward of *U*-band enables the parametrisation of GC properties with reasonable accuracy (Kaviraj et al. 2007a). The sensitivity of the ultraviolet (UV) spectrum to stellar age produces age constraints that are comparable to those achieved using spectroscopic methods, although the latter typically perform better for estimating metallicities (see Kaviraj et al. 2007a). The work presented here is the first to employ broadband UV-optical photometry from the WFC3 to study the properties of GCs in an early-type galaxy, and highlights the utility of this instrument for similar studies in the future.

This paper is organised as follows. We outline the construction of our GC sample in §2. §3 describes the methodology used for extracting ages, metallicities and stellar masses for individual GCs. We discuss the properties of the NGC 4150 GC system in §4 and summarise our findings in §5. A WMAP7 cosmology (Komatsu et al. 2011) is assumed throughout this paper.

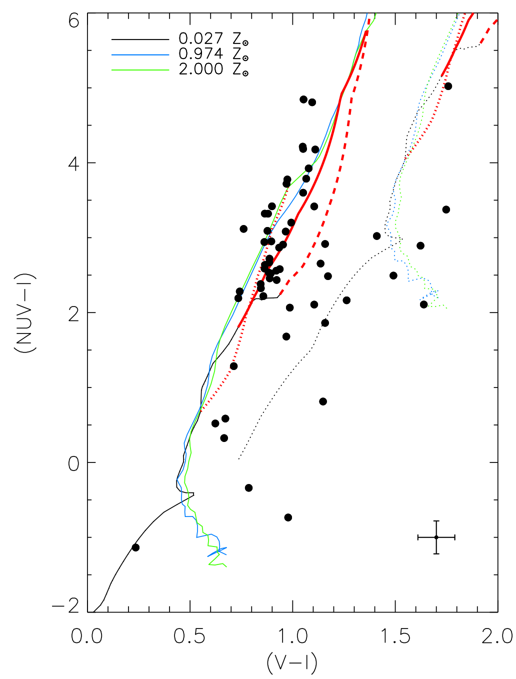


**Figure 1.** The observed photometry of the NGC 4150 GCs (corrected for Galactic extinction) overlaid on an example model UV-optical colour grid (an average error bar in indicated in the bottom-right corner). Tracks with different metallicities (in units of Z$_\odot$, see legend) are indicated using different colours. For each metallicity, the plotted ages range from 10 Myr to 15 Gyr. The solid grid represents a set of dustless models, while the dotted grid indicates models reddened using $E_{B-V} = 0.4$. The red dotted, solid and dashed curves are isochrones for 1, 5 and 15 Gyr respectively. Note that, at large ages ($\gtrsim$ 10 Gyr), the UV colours become bluer due to the onset of 'UV upturn' flux from old horizontal branch stars. The observed photometry is corrected for Galactic extinction.

## 2 SAMPLE CONSTRUCTION

The NGC 4150 images were processed using the `CALWFC3` software to bias, dark and flat-field correct the images (details of the WFC3 pipeline processing can be found in Windhorst et al. (2011)). The `MULTIDRIZZLE` software[1] was used to register individual exposures in a given filter, apply distortion corrections, mask out defects (e.g. cosmic rays) and combine the exposures using the drizzle image reconstruction technique (Fruchter & Hook 2002). A 'white-light' image was created by co-adding the *U*, *B*, *V*, and *I*-band images, from which point-like sources were identified using the `IRAF` task `DAOPHOT`. Circular aperture photometry within a 3-pixel radius was performed on the detected sources. Small wavelength-dependent corrections, based on the fraction of energy enclosed in the aperture, were applied to all magnitudes. We refer readers to Chandar et al. (2010) for more details of the source detection. The *V* and *I*-band images of each object were carefully visually inspected by SK and MC to remove contaminants e.g. foreground stars and background galaxies (which appear as diffuse and/or extended objects). This produced a sample of 63 GCs with $-10.5 < M_V < -5$ mag (consistent with the general range of GC luminosities found in ETGs, see e.g. Brodie & Strader 2006), with a median $M_V \sim -6.6$ mag. Note that the photometry presented in this paper is in the `VEGAMAG` system.

## 3 PARAMETER ESTIMATION

We assume that the observed WFC3 photometry of every GC in NGC 4150, after dereddening for Galactic extinction, can be parametrised by a 'simple stellar population' (SSP), which has a single age, metallicity and mass, and is attenuated by an internal line-of-sight extinction ($E_{B-V}$) in the host galaxy. The parameters for each GC are estimated by comparing its WFC3 ($NUV, U, B, V, I$) photometry to a large library of synthetic photometry, generated using SSPs taken from the Yi et al. (1997, Yi97 hereafter) stellar models, which have been extensively calibrated to the UV-optical properties of ETGs and Galactic GCs. Here we briefly note the salient properties of the models (we refer readers to Yi et al. (1997, 1998) for details). Main sequence

[1] http://stsdas.stsci.edu/multidrizzle/

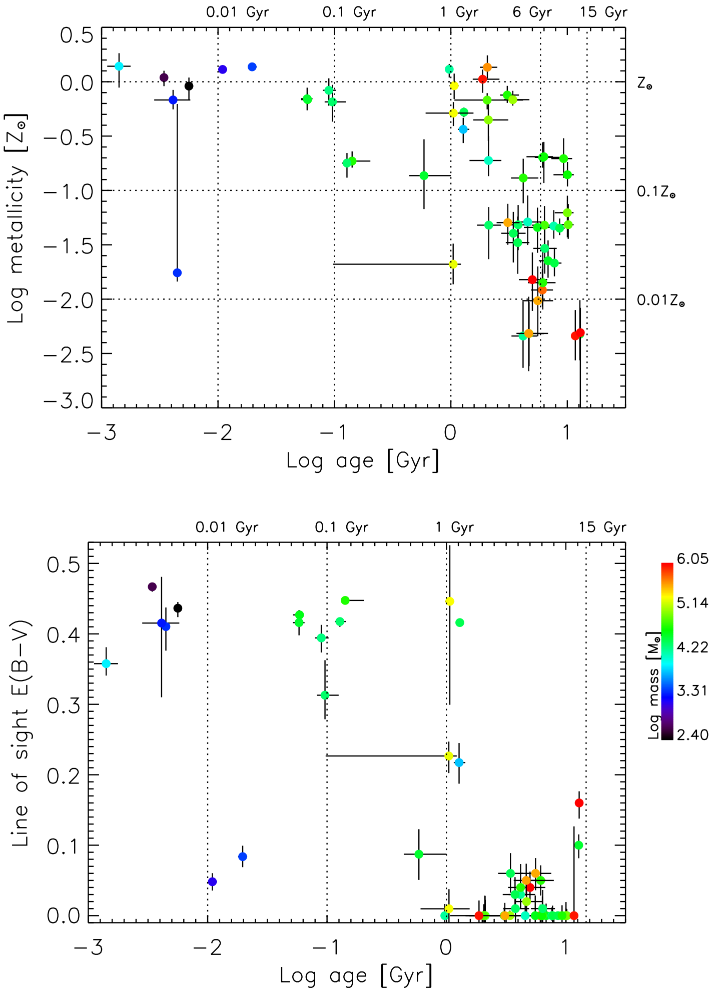


**Figure 2.** Ages and metallicities of individual GCs in NGC 4150. The error bars represent 'one-sigma' uncertainties, derived from the marginalised PDFs, as described in Section 3. These errors represent the combined uncertainty due to observational errors, uncertainties in the stellar models and degeneracies between parameters. Objects are colour-coded according to their estimated masses. The errors in the masses are ~0.3 dex.

and red-giant branch (RGB) evolution is synthesized using the Yonsei-Yale isochrones (Yi et al. 2001) using a Salpeter initial mass function (Salpeter 1955). Evolved stages - in particular the horizontal branch (HB), which drives the UV contribution from old stars - is modelled using Reimers' empirical mass-loss formula (Reimers 1975). The models apply a metallicity-dependent mass-loss efficiency on the RGB, which is constrained by both UV-optical colours of Galactic GCs and giant ellipticals (Yi et al. 1997) and hydrodynamical simulations (e.g. Willson et al. 1996). A gaussian mass dispersion on the HB is employed, constrained by the HB morphologies of Galactic GCs (e.g. Lee et al. 1990, 1994). Recent studies have exploited these models to quantify recent star formation in the nearby ETG population (Kaviraj et al. 2007c) and to explore the ages/metallicities of GC populations in NGC 5128 (Yi et al. 2004), M31 (Kaviraj et al. 2007a) and M87 (Kaviraj et al. 2007b).

The model grid used in this study spans the age range $0 - 14$ Gyr, the upper limit effectively set by the age of the Universe (Spergel et al. 2007). The metallicity range is 0.005 to 2.5 $Z_\odot$ (which are the limits of the stellar models), while the $E_{B-V}$ values span the range 0 to 1 mag. Models are reddened using the Calzetti et al. (2000) dust law, and the synthetic photometry for each model SSP is generated by convolving the spectrum with the correct WFC3 filter throughputs. Figure 1 shows the NGC 4150 GCs overlaid on an example model UV-optical colour grid.

For each GC, the free parameters (age, metallicity, mass and local extinction) are estimated by comparing its observed photometry (i.e. the $NUV, U, B, V, I$ magnitudes) to every model in the synthetic library, with the likelihood of each model ($\exp -\chi^2/2$) calculated using the value of $\chi^2$, computed in the standard way. The $\chi^2$ uncertainties are calculated by adding, in quadrature, the observational errors and model uncertainties, which are assumed to be 0.05 mag for all optical filters and 0.1 mag for the $NUV$ (Yi 2003). From the joint likelihood distribution, each parameter is marginalised to compute its one-dimensional probability density function (PDF). We take the median value of this PDF to be the best estimate of the parameter in question and the 16 and 84 percentile values as the 'one-sigma' errors on this estimate. These errors represent the combined uncertainty due to observational errors, uncertainties in the stellar models and degeneracies between parameters.

## 4 PROPERTIES OF GCS IN NGC 4150

It is worth recalling first that NGC 4150 is a low-mass ETG in a low-density environment, which is also a recent merger remnant (C11). Studies using integrated spectrophotometry show that the peak epoch of stellar mass assembly and the timescales of star formation in ETGs are both strong functions of the stellar mass and local environment of the galaxy in question. In particular, the star-formation histories (SFHs) of low-mass ETGs such as NGC 4150 ($M_* \sim 6.3 \times 10^9$ $M_\odot$) are expected to be significantly different from that of their massive counterparts. While massive ETGs (especially those that inhabit galaxy clusters) form the bulk of their stars at high redshift ($z > 2$), ETGs similar to NGC 4150 form a significant fraction of their stars at $z < 1$ (e.g. Brinchmann & Ellis 2000; Jimenez et al. 2005; Kaviraj et al. 2008), with SFHs that probably peak 6-7 Gyr in the past (e.g. Thomas et al. 2005) i.e. at $z \sim 0.7 - 0.8$ in a WMAP7 cosmology. Under the reasonable assumption that GC formation follows the overall stellar mass assembly, one therefore expects a population of GCs in NGC 4150 to have formed around this epoch. Furthermore, since there is unambiguous evidence for merger-driven star formation within the last Gyr (C11), one may also expect a population of clusters to have formed on those timescales.

Figure 2 indicates that the properties of the NGC 4150 GC population are generally consistent with these expectations (note the log axes in this figure). We find that, in addition to a small population of GCs older than ~11 Gyr, there exists a dominant population of clusters with ages centred around ~6 Gyr. These GC populations are metal-poor, with metallicities less than $\sim 0.1 Z_\odot$. Furthermore, there is evidence for the presence of a population of young, metal-rich (metallicity $> Z_\odot/3$) clusters which has formed within the last Gyr. Not unexpectedly, the old and intermediate-age GCs reside in regions of low extinction (typically $E_{B-V} < 0.05$ mag), while the young GCs reside in regions of higher ambient dust content (typically $E_{B-V} > 0.3$ mag).

The metallicities of the young GCs are in good agreement with the metallicity of the young stars in the field derived by C11, which are in the range $0.3Z_{\odot}$ to $0.8Z_{\odot}$. Figure 3, which shows the locations of the GCs studied in this paper, indicates that the young clusters are spatially coincident with the *NUV*-bright region in the galaxy core which hosts the recent star formation (shown by the inset, see also Figure 3 in C11). In comparison, the dominant intermediate-age GC population is spread uniformly in the inner halo of the galaxy. Together with the similarity in the metallicities of the young clusters and the recently-formed field stars, this suggests that the young GCs are indeed products of the recent minor merger experienced by NGC 4150.

While the lack of a dominant population of very old GCs (ages > 11 Gyr) is consistent with the properties of the field stars in faint ETGs such as NGC 4150, we have checked that such a population of clusters would indeed be detectable in our imaging. To probe this issue, we have explored the properties of a hypothetical GC population with an age of 12 Gyr, extrapolated from the observed GCs which have ages centred around ∼6 Gyr. Using the observed GCs as a guide allows us to consider a realistic distribution of metallicities, dust contents and masses for this hypothetical population. For each observed GC in our sample, we predict the photometry of a corresponding 12-Gyr-old cluster, which has an identical metallicity, ambient dust content and stellar mass. We find that the predicted magnitudes of these hypothetical GCs (in both the optical and *NUV* filters) lie well within the range of values of the observed clusters extracted from the WFC3 images. It is unlikely that a population of very old GCs in this galaxy remains undetected in the WFC3 images and thus the ages and metallicities derived here are likely to be an accurate representation of the stellar mass assembly of NGC 4150. Note that very old GCs are indeed part of our sample, albeit in small numbers. It is worth noting, in the context of the wider literature, that most GC systems studied so far inhabit *massive* ETGs. Not unexpectedly, the dominant clusters in these galaxies are old, mirroring the old age of their stellar populations. However, in galaxies such as M33 and the Large Magellanic Cloud, in which star formation is not restricted to high redshift, intermediate-age GCs are commonly found (e.g. Cohen et al. 1984; Searle et al. 1980; Frogel et al. 1990), akin to our findings in NGC 4150.

Finally, we discuss the small population of (low-mass) young clusters with ages < 0.1 Gyr that are found in the central regions of NGC 4150. Within the first few $10^8$ yr after formation, cluster disruption is dominated by constant number loss, with ∼80-90% of clusters disrupted every dex in time (e.g. Whitmore et al. 2007; Whitmore 2009; Fall et al. 2009; Mora et al. 2009). The subsequent evolution of clusters is determined by two-body relaxation, which results in constant mass loss during each unit of time, with $10^{-5}$ M$_{\odot}$ yr$^{-1}$ providing acceptable fits to the available GC literature (e.g. Fall & Zhang 2001). Thus, while the dominant population of old GCs in NGC 4150 are long-lived objects, the bulk of the young GCs are likely to be a transient population that will largely dissolve within a few $10^8$ yr. It is worth noting that the constant number-loss scenario implies that the

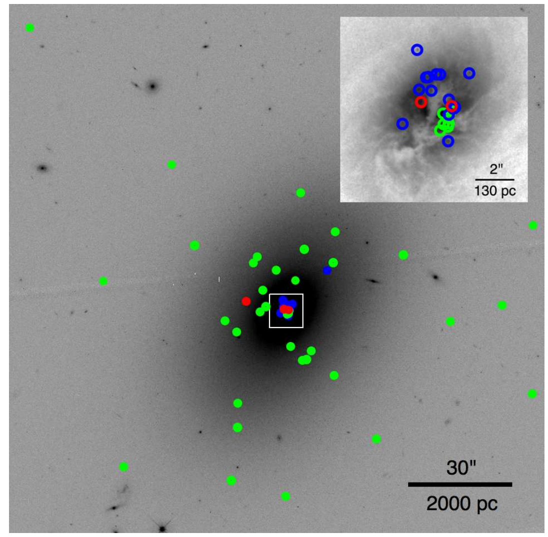


**Figure 3.** The locations of GCs in NGC 4150, colour-coded according to their ages, overplotted on a *B*-band image of NGC 4150. Red circles indicate clusters with ages greater than 11 Gyr, green circles indicate GCs with ages between 1 and 11 Gyr and blue circles indicate young clusters, with ages less than 1 Gyr.

distribution of clusters younger than a few $10^8$ yr is skewed towards the *youngest* clusters, since they have had the least time to be disrupted.

## 5 SUMMARY

We have used the new *Wide Field Camera 3* (WFC3) on board the *Hubble Space Telescope* (HST) to study the globular cluster system in NGC 4150, a sub-L* ($M_B \sim -18.48$ mag) early-type galaxy that resides in a low-density environment. A recent spatially-resolved WFC3 study of its field stellar population demonstrates that this galaxy is a recent minor-merger remnant, the accretion event contributing a few percent to the current stellar mass of this galaxy within the last Gyr (C11). In this study we have employed broadband ($NUV, U, B, V, I$) WFC3 photometry (covering 2000-9000 Å) to estimate individual ages, metallicities, masses and line-of-sight extinctions ($E_{B-V}$) for 63 bright ($M_V < -5$ mag) GCs in this galaxy.

The peak epoch of stellar mass assembly and the timescale of star formation is known to vary with both the mass and local environment of the ETG in question. The SFHs of low-mass ETGs like NGC 4150 are expected to peak around 6-7 Gyr in the past (as opposed to 10-12 Gyr in their massive counterparts). Furthermore, it is reasonable to expect the GC population to reflect the recent merger-driven star formation in NGC 4150. The derived properties of the GCs in this galaxy are in good agreement with these expectations. In addition to a small population of GCs older than ∼10 Gyr, we find a dominant population of clusters with ages centred around ∼6 Gyr. These GC populations are metal-poor, with metallicities less than $0.1Z_{\odot}$, and reside in regions of low extinction ($E_{B-V} < 0.05$ mag). We also find a population of young, metal-rich (metallicity $> 0.3Z_{\odot}$ mag) clusters formed within the last Gyr, which reside in regions of relatively high ambient extinction ($E_{B-V} > 0.3$). The derived metallicities of these young GCs is in good agreement with the metallicity of the young field stellar populations derived by C11. The young clusters are spatially coincident with the *NUV*-bright region of the galaxy core which hosts the star formation, strongly suggesting that they are indeed products of the recent minor merger. Cluster disruption models suggest that, while the old and intermediate-age GCs in NGC 4150 are long-lived objects, the young GCs are a transient population that will largely disappear within a few $10^8$ yr.

This *Letter* demonstrates the utility of UV-optical photometry from the WFC3 for determining GC age and metallicity distributions, which are useful proxies for the cosmic star-formation and chemical-enrichment history of their host galaxies. WFC3's large UV field-of-view and high spatial resolution makes it the only instrument capable of such investigations in the nearby Universe. This study will serve as a precursor to a forthcoming systematic investigation of GC populations using UV-optical photometry in a representative sample of local ETGs (HST Programme 12500, PI: Kaviraj). Looking further ahead, the revolutionary spatial resolution of the 'extremely large telescopes' will, in principle, allow us to implement similar techniques, based on (rest-frame) UV-optical photometry, to study GC populations in the intermediate redshift ($z > 0.4$) Universe.

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